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The voltage and current at any position in a transmission-line pulser can be calculated from arbitrary voltage and current pulse shapes measured at one position in the pulse line. A simple closed-form method for doing this is discussed. This method is particularly amenable to a computer-driven transient-digitizer system. At the Harry Diamond Laboratories Aurora Facility this method is implemented in the PDP 11/60 program, VANDALS, and is used for the inter-comparison of sensors along the transmission path in the vacuum region of the pulser. For slowly varying pulses this method is seen to reduce to the addition of an inductive correction term to the measured voltage.

HDL-TM-84-8

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Pulsed-Power System Diagnostics: Electromagnetic Data Interpretation Along Pulse Lines

by George A. Huttlin

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and Development Command
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1. INTRODUCTION

Two of the primary pieces of the diagnostic information in pulsed-power experiments are the voltage and the current provided by the pulser at the load. In many instances, particularly with voltages on vacuum devices, it is not possible to make measurements as close to the load as one would like. Often an inductive correction is used to relate the voltage sensed at one position to the actual voltage at the position of interest. However, such a correction is only an approximation with limited validity.

A better method to infer the voltage and current at some position from data measured at another position uses a transmission-line circuit and a transmission matrix approach. There are three requirements for the application of this method: first, the voltage and current must be sensed at a common position; second, the record of these data must include information before and after the time frame of interest by a time equal to the transit time from the sensors to the calculation position; and, third, the geometry connecting the calculation position with the data position must be characterized by a system of transmission lines.

One necessity for the practical implementation of this method is a computerized system for pulsed digitization and data processing. With the more widespread use of high-speed transient digitizers, this otherwise awkward (and therefore little-used) method is quite easy to implement.

2. ANALYSIS

For our purposes we consider that the region connecting the field sensors with the position of interest can be described by a sequence of lossless transmission lines each described by an impedance, Z_i, and a one-way transit time, T_i.

In each transmission line there can be a wave propagating to the right and to the left, and each wave has a frequency-independent speed. For the right-going wave of voltage, $\vec{V}$, the current at a given point in the line is given by $\vec{V}/Z$, while for the left-going wave, $\overleftarrow{V}$, the current is $-\overleftarrow{V}/Z$. Consequently, the total current, I, is given by $I = \left(\vec{V} - \overleftarrow{V}\right)/Z$, whereas the total voltage is given by $V = \vec{V} + \overleftarrow{V}$. Combining the expressions, one can express the traveling waves in terms of I and V:

$$\vec{V} = \frac{1}{2}(V + ZI)$$

and (1)

$$\overleftarrow{V} = \frac{1}{2}(V - ZI) \quad .$$

We assume we know as functions of time the voltage, V_i, and current, I_i, to the left of the ith transmission line (fig. 1). What we want to determine are the functions, V_{i+1} and I_{i+1}, which describe the voltage and current to the right of the transmission line.

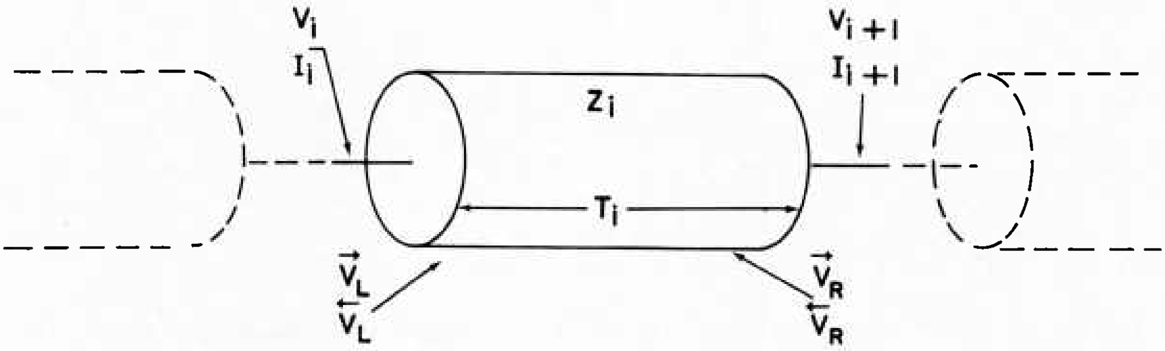

Figure 1. Definition of the parameters: V_i and I_i are the total voltage and current to the left of the ith transmission line; V_{i+1} and I_{i+1} are the total voltage and current to the right; $\overrightarrow{V}_L$ and $\overleftarrow{V}_L$ are, respectively, the right- and left-going voltage waves in the ith transmission line at its left end; and $\overrightarrow{V}_R$ and $\overleftarrow{V}_R$ are, respectively, the right- and left-going voltage waves in the same line at its right end.

At a given time, t, the voltage and current to the right of the transmission line are expressed by

$$V_{i+1}(t) = \overrightarrow{V}_R(t) + \overleftarrow{V}_R(t)$$

and (2)

$$Z_i I_{i+1}(t) = \overrightarrow{V}_R(t) - \overleftarrow{V}_R(t) \quad ,$$

in which the subscript R identifies the traveling waves as they appear in the right end of the ith transmission line. These values, $\overrightarrow{V}_R$ and $\overleftarrow{V}_R$, at time t are equal to the left-end values, $\overrightarrow{V}_L$ and $\overleftarrow{V}_L$, at times offset by the transit time, T_i:

$$\begin{aligned} \overrightarrow{V}_R(t) &= \overrightarrow{V}_L(t-T_i) \quad , \\ \overleftarrow{V}_R(t) &= \overleftarrow{V}_L(t+T_i) \quad . \end{aligned} \tag{3}$$

Using equation (1), we can express the time-offset traveling voltages at the left side in terms of the total voltage and current measured there:

$$\overrightarrow{V}_L(t-T_i) = \frac{1}{2}V_i(t-T_i) + \frac{1}{2} Z_i I_i(t-T_i)$$

and (4)

$$\overleftarrow{V}_L(t+T_i) = \frac{1}{2}V_i(t+T_i) - \frac{1}{2} Z_i I_i(t+T_i) \quad .$$

We now combine equations (4), (3), and (2) and obtain the expressions desired for $V_{i+1}(t)$ and $I_{i+1}(t)$ in terms of the known functions, V_i and I_i:

$$V_{i+1}(t) = \frac{1}{2}\left[V_i\left(t-T_i\right) + Z_i I_i\left(t-T_i\right) + V_i\left(t+T_i\right) - Z_i I_i\left(t+T_i\right)\right] \quad , \tag{5a}$$

$$I_{i+1}(t) = \frac{1}{2}\left[V_i\left(t-T_i\right) + Z_i I_i\left(t-T_i\right) - V_i\left(t+T_i\right) + Z_i I_i\left(t+T_i\right)\right]/Z_i \quad . \tag{5b}$$

Equations (5a) and (5b) embody the result of the transmission operation through one element of the circuit and are the equations used in the computer application of this method.

For geometries that can be described by a series of transmission lines of a variety of impedances, equations (5a) and (5b) can be used to step from one junction to the next until the voltage and current are derived for the position of interest. In carrying out this procedure neither V nor I nor the geometry need be specified to the left of the point at which V and I are measured or to the right of the position of interest. Consequently, derived data can be used directly to indicate the load characteristics.

According to equations (5a) and (5b), to derive V_{i+1} or I_{i+1} at a time, t, the given V_i and I_i must both be known at times $t + T_i$ and $t - T_i$. This requirement chains itself across a succession of transmission lines so that the derived data are less extensive than the measured data at each end of the trace by the sum of the individual T_i.

3. RELATION TO OTHER DATA-CORRECTION FORMULAS

The result contained in equations (5a) and (5b) should, with the proper assumptions, simplify giving the inductive correction term $L\dot{I}$ if certain simplifying assumptions can be made. To investigate what these assumptions might be, we write equation (5a), grouping together the voltage and current terms:

$$V_{i+1}(t) = \frac{1}{2}\left[V_i\left(t-T_i\right) + V_i\left(t+T_i\right)\right] - T_i Z_i\left[I_i\left(t+T_i\right) - I_i\left(t-T_i\right)\right]/\left(2T_i\right) \quad . \tag{6}$$

The factor $T_i Z_i$ seen above is identically the inductance L_i of the ith transmission line. If the variation in time of V_i is approximately linear from $t - T_i$ to $t + T_i$, then $1/2\left[V_i\left(t-T_i\right) + V_i\left(t+T_i\right)\right]$ approximates $V_i(t)$. Furthermore, if the same condition holds for I_i, then $\left[I_i\left(t+T_i\right) - I_i\left(t-T_i\right)\right]/\left(2T_i\right)$ approximates $\dot{I}_i(t)$. If both V_i and I_i are approximately linear over $t - T_i$ to $t + T_i$, we see that equation (6) reduces to

$$V_{i+1}(t) \simeq V_i(t) - L_i\dot{I}_i(t) \quad . \tag{7}$$

Consequently, if the assumption of linearity over a time, $2T_i$, can be made, the standard $L\dot{I}$ correction is valid using sensors of voltage and current at the same position.

Analogously, to the extent that V_i and I_i are linear from $t - T_i$ to $t + T_i$, equation (5b) reduces to

$$I_{i+1}(t) \simeq I_i(t) - C_i\dot{V}_i(t) \quad , \tag{8}$$

where C_i is the capacitance of the transmission line.

4. IMPLEMENTATION IN VANDALS PROGRAM AT AURORA

VANDALS is a program implemented on the Aurora[1] PDP 11/60 computer to process voltage and current data recorded with Tektronix 7912 transient digitizers and their associated software. Although VANDALS performs other tasks associated with digitized data-taking (e.g., baseline and sweep-speed adjustment; time alignment; integration of traces from capacitive voltage dividers and B-dot loops; and calculation of wave impedance, power, energy, and IV**2.8), its main function is to implement the translation algorithm discussed above.

The relevant portion of the VANDALS subroutine that performs the translation appears in appendix A. The transmission-line circuit in VANDALS is a string of up to 30 transmission lines of arbitrary impedances, Z(J), and transit times, T(J). At Aurora this circuit (fig. 2) describes the region of the machine from the high-voltage end of the vacuum insulator stack to the field-emission load. The transit times of the circuit elements were chosen so that the various voltage and current monitors and the load are positioned at junctions in the circuit.

The voltage and current traces to be translated are contained in the arrays V1 and I1, each of which is dimensioned for 768 points. These data arrays are associated with any one (N) of the 31 positions between (or at the end of) transmission lines in the circuit. Things are set up so that position N is between lines N and N + 1. Position 30 is between line 30 and the nonexistent line 31; position 0 is between line 1 and the nonexistent line 0. Each pass through the major DO loop (ends at statement 200) replaces the data in the arrays V1 and I1 with data appropriate to either position N + 1 or position N - 1. The formalism of the algorithm will permit translations in either direction in the circuit provided an adjustment is made in the sign of current terms in the statements corresponding to equations (5a) and (5b) above. This must be done because the definition of positive current implies a directionality in the circuit. The factor SIGN which takes the value +1 or -1, as appropriate, takes care of this.

As explained in the theory section above, to calculate a point for time t in a translation across a line, J, of length T(J), data must exist in V1 and I1 corresponding to both t + T(J) and t - T(J). This means that, if in V1 and I1 the data cover the time span from t_1 to t_2, the translated data (which are temporarily put in the scratch arrays V2 and I2) will cover the time span from

[1] *B. Bernstein and I. D. Smith, Aurora, and Electron Accelerator, IEEE Trans. Nucl. Sci., 20 (June 1973), 294.*

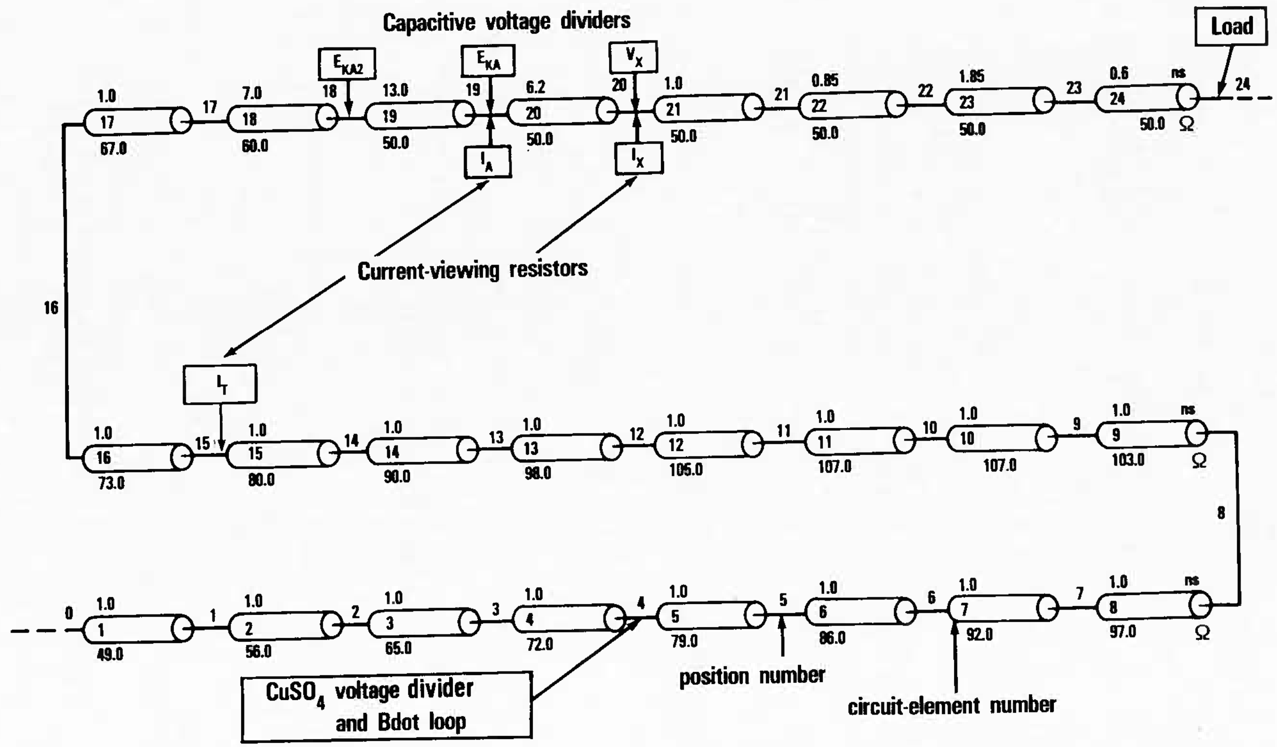

Figure 2. The Aurora sensor/load data-correlation circuit.

$t_1 + T(J)$ to $t_2 - T(J)$. Therefore, in successive translations the time span covered by the data will shrink. The program keeps track of this with the quantities K1 = NMN and K2 = NMX, which are the respective numbers of the minimum and maximum bins of relevant data.

Since the program permits transit times of arbitrary values, an interpolation is done between points in V1 and I1 to get quantities V1(t±T(J)) and I1(t±T(J)) for use in the translation formulas. A graphical illustration of this interpolation procedure is commented into the listing (app A) in which all parameters of relevance are identified. For our purposes a linear interpolation has been found to be quite adequate; but, as a result of this interpolation, the data are smoothed in translation. This smoothing can be seen in the sample Aurora data of figure 3. Also shown in figure 3 is the shortening of the traces due to the algorithm. This shortening is at both ends, although one could reason that it need not be for times before the pulse, if we assume we know *a priori* what the current and voltage are before the time frame of the recorded data. As the original current trace can be seen here to end slightly before the voltage trace, in this example it is the extent of the original current data that governs the extent of data in subsequent calculations.

5. TEST OF THE TRANSLATION ALGORITHM

To test the coding of the basic translation algorithm, a simple sine-wave example is presented, with a very simple circuit.

Consider a 50-Ω transmission line that is 100 ns long and is represented by a chain of twenty-five 50-Ω transmission lines, each 4 ns long. At one end of this line some unspecified circuitry is attached. This circuitry results in a voltage of 50-V amplitude that is exactly in phase with the current of 1 A at this particular end of the transmission line. The voltage and current are sinusoids with a 250-ns period.

At the remote end we expect identical waveforms except that they are delayed by 100 ns. The load responsible for V(t) and I(t) must be a resistance of 50 Ω (or a further length of 50-Ω cable terminated in 50 Ω).

Figure 4(a) shows the given voltage and current. Figure 4(b) shows the voltage and current calculated for the other end of the 100-ns line. Note that, as expected, the traces are identical in shape to the given data but delayed by 100 ns. Also note that the traces are shorter by about 120 ns at each end. Theoretically, the data should be shortened by one transit time or 100 ns at each end. The extra 20 ns is due to a rounding effect: on each pass through one of the 25 transmission lines, the data are shortened by an integral number of data points. When the transit time is 4 ns and the 512 data points are 0.98 ns apart, 4.1 data points should be eliminated per transmission line at each end of the trace. To round 4.1 down to 4 data points would leave an irrelevant point at each end of each trace. Therefore, 5 data points are eliminated instead; (5 points) × (0.98 ns/data point) × (25 lines) accounts for 122 ns lost at each end of each trace. This effect has proven to be no problem with real data (fig. 3).

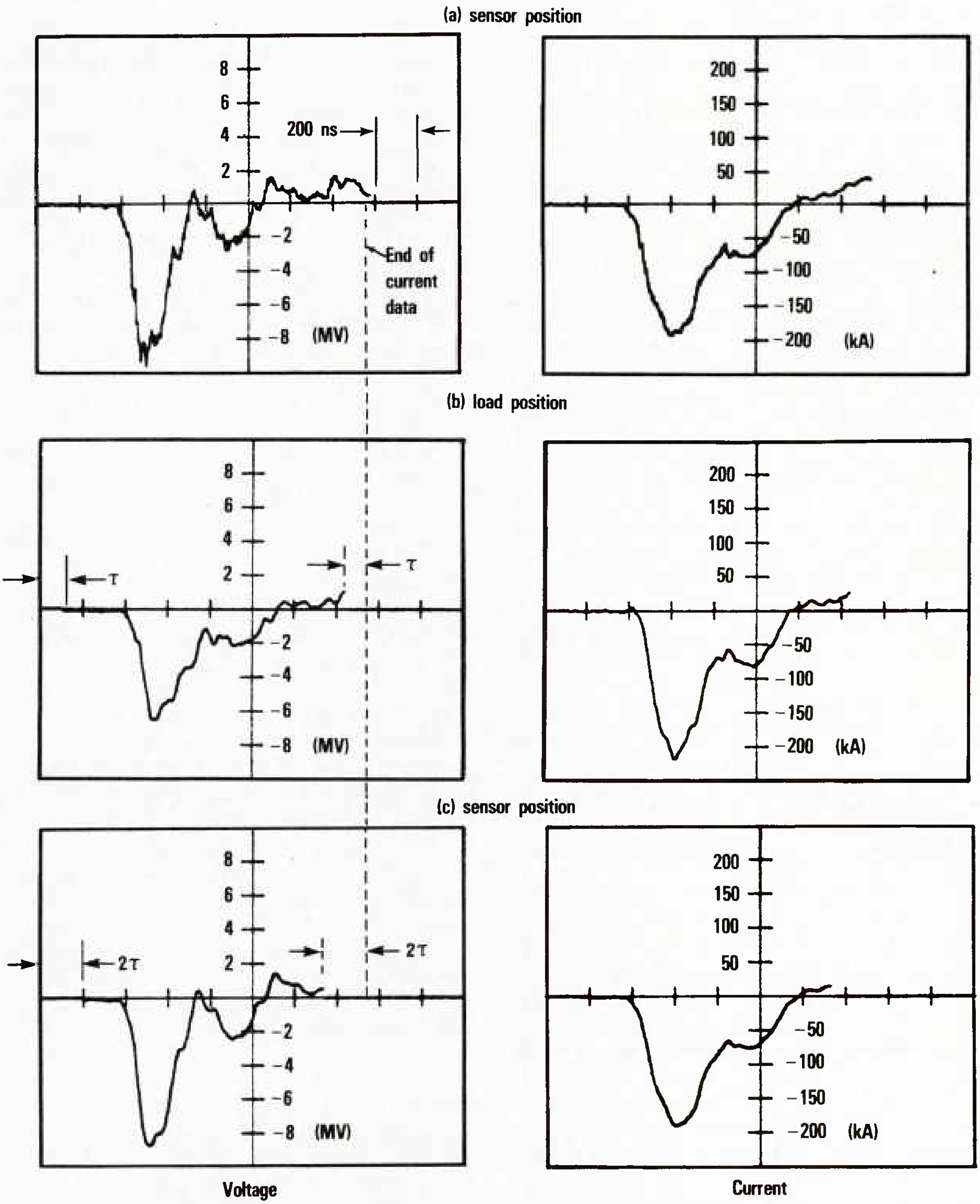

Figure 3. Sample Aurora data: (a) data provided by the sensors, (b) data calculated for the load position with the use of the data of 3(a), and (c) data calculated for the sensor position based on the calculated load-position data of 3(b). Ideally this would reproduce exactly the data in 3(a), but is smoothed due to interpolation.

6. CONCLUDING REMARKS

Legitimately, one can only make use of the equations (5a) and (5b) if V and I are known functions of time at some common position. However, if experience indicates that either V or I does not vary too much in position, one could rationalize applying this method to two traces from slightly different positions along a transmission line. The present method of analysis, which assumes that the two traces originate at the same position along a transmission line, results in a closed form (equations (5a) and (5b)) for translating the traces. One could envision converging infinite series replacements for equations (5a) and (5b) so that information for a third position could be unfolded rigorously from monitors at two different positions. An approach to this problem was taken by R. Richardson et al. of Maxwell Laboratories, Inc. in reference to work on their Blackjack 5 Machine.[2]

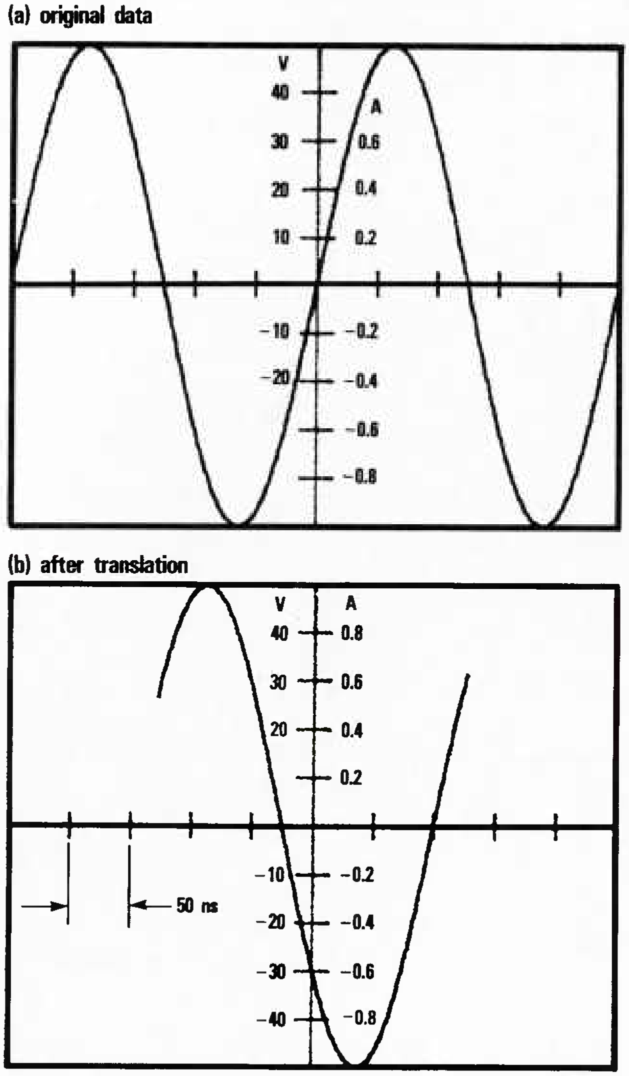

Figure 4. Sinusoidal test of code: (a) data simulated for "sensor" position and (b) data calculated (using VANDALS) 100 ns downstream of original data through twenty-five 4-ns transmission lines. The extra time missing at each end of the calculated data results from rounding up the fractional number of bins that should be removed from the data on each pass.

---

[2] *R. Richardson, E. Chu, W. Clark, J. Shannon, and M. Wilkinson, Calibration of the Blackjack 5 Pulse Generator Output Power, National Bureau of Standards Special Publication 628, Measurement of Electrical Quantities in Pulse Power Systems, R. H. McKnight and R. E. Hebner, Jr., ed.(June 1982), 150.*

APPENDIX A.--THE TRANSLATION CODING

```
C
C
C                                                                      MPLUS+1
C                                                                         :
C                                                  K                      :
C                                   MMINUS+1       :                      :
C                                      :           :         MPLUS        :
C                                      :           :           :          :
C                          MMINUS      :           :           :          :
C                            :         :           *           :          :
C                            :         :     *     :       --->:  :<---SECOND TBTWN
C          FIRST TBTWN--->:      :<---        :           :  :       :
C                            :     :  :           :     *     :  :       :
C                            :     :  :           :           :  :       :
C                            :     :  *           :           :  :       :
C TIME=0      VMINUS         :     :  :           :           *  :       :
C   :            OR-------->X  :           :           :  :       :  VPLUS
C   :         IMINUS         :     :  :           :           :  X<------OR
C   :                        :     :  :           :           :  :       :  IPLUS
C   :                        :     :  :           :           :  :       :
C   :                        *     :  :           :           :  :       :
C   :-----*-----*-----+-----+-----+-----+-----+-----+-----*-----+-----*-
C   :     1     2     3    :  4     5     6     7     8  :  9    10    11
C   :                      :                             :        *
C   :                      :                             :
C   :<------TMINUS-------->:<---T(J)---->:<----T(J)--->:
C   :                                    :             :
C   :                                    :             :
C   :<--------------K*DT--------------->:             :
C   :                                                  :
C   :                                                  :
C   :<----------------------TPLUS-------------------->:
C
C   THE GRAPHIC EXAMPLE SHOWS EITHER A VOLTAGE OR CURRENT DATA ARRAY
C   THAT IS TO CONTRIBUTE TO A DATA TRANSLATION.  THE NUMBERS IDENTIFY
C   THE BINS.  EACH * IS A DATA POINT IN THAT ARRAY.  THE SYMBOL
C   X SHOWS THE LINEARLY INTERPOLATED VALUES USED IN THE ALGORITHM
C   (STATEMENT 100 AND THE ONE JUST ABOVE IT) THAT ACCOMPLISHES THE
C   TRANSLATION.
C
C
C   K1 AND K2 ARE THE RESPECTIVE SCRATCH EQUIVALENTS OF NMN AND NMX.
C
  300 K1= NMN
      K2= NMX
C
C   THE SCRATCH ARRAYS V2 AND I2 ARE ZEROED.
C
      DO 99 K= 1, 768
      V2(K)= 0.
   99 I2(K)= 0.
```

```
C
C   POSITIVE CURRENT IS ASSUMED TO BE IN THE DIRECTION OF INCREASING
C   VALUES FOR THE SUBSCRIPT J IN Z(J) AND T(J).  SIGN IS A FACTOR + OR -1
C   USED AS THE SIGN OF THE CURRENT TERMS IN THE TRANSLATION ALGORITHM.
C   TO USE THE ALGORITHM FOR TRANSLATIONS IN THE DIRECTION OF INCREASING
C   J, SIGN IS +1; TO USE THE ALGORITHM FOR TRANSLATIONS IN THE OTHER
C   DIRECTION, SIGN IS -1.
C
      SIGN= 1.
      IF(N1 .GT. N2) SIGN= -1.
      IF (N1 .EQ. N2) GO TO 1000
      NUMBER= ABS(N2-N1)
C
C   THE LOOP OVER CIRCUIT ELEMENTS BEGINS.
C
      DO 200 JJ=1, NUMBER
C
C   J IS THE I.D. NUMBER OF THE ELEMENT BEING CALCULATED ACROSS.
C   IMPLICIT HERE IS THAT TO THE RIGHT OF POSITION J IS ELEMENT J+1.
C
      J= JJ + N1
      IF(N1 .GT. N2) J=N1+1-JJ
C
C   DT IS THE TIME PER BIN.
C   THE IDENTIFIERS K1 AND K2 OF THE MINIMUM AND MAXIMUM BINS OF RELEVANT
C   DATA ARE ADJUSTED BELOW.  IF T1 (T2) IS THE TIME AT WHICH THE DATA
C   BEGINS (ENDS) BEFORE TRANSLATION, T1+T (T2-T) IS THE TIME AT WHICH
C   THE DATA BEGINS (ENDS) IN THE NEW TRANSLATED DATA ARRAY.
C
      K1= 1 +  K1+T(J)/DT
      K2= K2-T(J)/DT
      IFLAG = 0
      IF (K2 .GT. K1) GO TO 10
      WRITE (5, 11)
   11 FORMAT (' THE SPAN OF THE DATA IS TOO RESTRICTED FOR FURTHER',
     1 ' TRANSLATION.')
      IFLAG = 1
      GO TO 1000
C
C   K1 AND K2 ARE RESPECTIVELY THE LOWEST AND HIGHEST BINS OF RELEVANT
C   DATA.  THE LOOP OVER BINS IN THE CALCULATED DATA ARRAYS BEGINS HERE.
C
   10 DO 100 K= K1,K2
      TMINUS= K*DT-T(J)
      MMINUS= TMINUS/DT
      TBTWN= TMINUS - MMINUS * DT
      VMINUS= V1(MMINUS)+TBTWN*(V1(MMINUS+1)-V1(MMINUS))/DT
      IMINUS= I1(MMINUS)+TBTWN*(I1(MMINUS+1)-I1(MMINUS))/DT
      TPLUS= K*DT+T(J)
      MPLUS= TPLUS/DT
      TBTWN= TPLUS-MPLUS*DT
      VPLUS= V1(MPLUS)+TBTWN*(V1(MPLUS+1)-V1(MPLUS))/DT
      IPLUS= I1(MPLUS)+TBTWN*(I1(MPLUS+1)-I1(MPLUS))/DT
```

```
C
C   THE NEXT TWO STATEMENTS DO THE ACTUAL TRANSLATION.
C
      V2(K)= .5*(VMINUS+SIGN*Z(J)*IMINUS+VPLUS-SIGN*Z(J)*IPLUS)
  100 I2(K)= .5*(SIGN*VMINUS+Z(J)*IMINUS-SIGN*VPLUS+Z(J)*IPLUS)/Z(J)
C
C   THE TRANSLATED DATA IN THE SCRATCH ARRAYS ARE TRANSFERRED TO THE
C   ORIGINAL ARRAYS AND THE SCRATCH ARRAYS ARE ZEROED.
C
      DO 200  K=1, 768
      V1(K)=V2(K)
      V2(K)=0.
      I1(K)=I2(K)
  200 I2(K)=0.
C
C   THE LOWEST AND HIGHEST RELEVANT DATA BINS (NMN AND NMX) ARE SHIFTED
C   SINCE DATA IS LOST AT EACH END OF THE TRACE BY AN AMOUNT CORRESPONDING
C   TO THE TRANSIT TIME OF THE TRANSLATION.
C
      NMX= K2
      NMN=K1
 1000 RETURN
      END
```

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